Original scientific paper

Impact of Distance between Strip Roads on Productivity and Costs of a Forwarder in Commercial Thinning of *Pinus Taeda* Stands

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Abstract

Demand for higher value-added wood products stimulates research for new, mainly mechanized, thinning operations in order to increase productivity and reduce production costs. In this context, the aim of this study was to evaluate the impact of distance between strip roads on forwarder productivity and costs of thinning operations in Pinus taeda stands. The study was carried out in 10-year-old Pinus taeda *stands located in Parana State, Brazil. Two thinning methods were evaluated: (1) TH5: systematic harvest in every fifth tree row and selective harvest in adjacent rows; and (2) TH7: systematic harvest in every seventh tree row and selective harvest in adjacent rows. Working cycle times, productivity and costs were determined through a time-motion study of the forwarder. The additional variables evaluated were wood assortments (industrial wood and energy wood) and extraction distances (50, 100, 150 and 200 m), and mean values were compared between thinning methods using t tests for independent samples (α=0.05). Loading and unloading elements consumed the most time in the working cycle, with lower participation time in TH7 due to greater availability of logs along the strip roads (higher pile volumes), influencing total cycle time up to the mean distance of 150 m for both assortments. TH7 consequently showed 6% higher productivity, its energy yield was 5.3% lower and its production cost was 3.0% lower.*

Keywords: thinning operations, pine, forwarding distance, pile volume

1. Introduction

Thinning is a well-recognized treatment in order to improve increment and quality of the remaining trees (Lamprecht 1990, Campos and Leite 2017). Thinning in Brazil is usually done by the mixed method of full tree row harvest in the stand and selective cutting of trees in adjacent rows (Lopes et al. 2017). Therefore, using mechanized operations becomes a complex task due to the large number of factors that hinder the operation, directly influencing forest machine productivity and consequently operation costs (Malinovski et al. 2006).

Wood harvesting operations in thinnings can be influenced by operational characteristics, mainly by the machine traffic inside the stand and the distance traveled by the machine in order to avoid damaging the remaining trees. Additionally, lower timber volume and assortments with lower commercial value are usually removed in selective thinning (Lopes et al. 2016, Acuña et al. 2018, Cabral et al. 2018, Lopes et al. 2018, Rodrigues et al. 2018).

Thinning operations are generally cut to length (CTL) systems and the design of thinning operation mainly depends on the crane reach (Lamprecht 1990, Spinelli and Nati 2009). Every fifth tree row is usually cut and selective cutting is performed in the adjacent tree rows. However, it is possible to apply large distance between strip roads with the combined use of harvesters and chainsaws, or only machines with larger crane reach (Mederski 2006 and 2018). While providing benefits in the productive characteristics of the forest stand, this increase can also provide improvements in the operational aspects of wood harvesting.

When wood extraction is performed by a forwarder in CTL technology, its operational performance can be affected by several variables: mean wood extraction

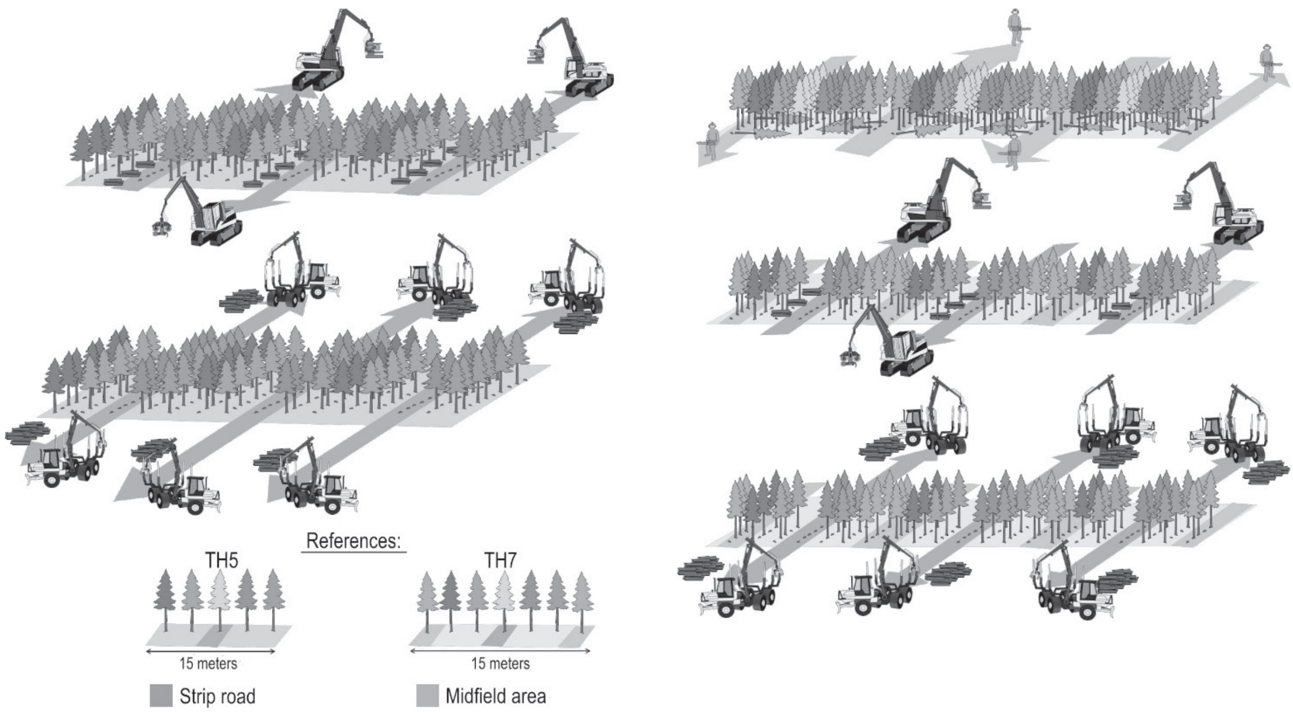

Fig. 1 Spatial distribution of strip roads and thinning operation stages in TH5 and TH7

distance, pile volume formed in the pre-extraction stage by the harvester, and number of assortments (Simões and Fenner 2010, Carmo et al. 2015, Mazão et al. 2017). The employed thinning model can directly affect these variables, since the greater the distance between road lines traveled, the greater the wood availability.

The aim of this study was to evaluate the impact of distance between strip roads on forwarder productivity and costs in implementing two thinning models in *Pinus taeda* stands. Two thinnings were proposed: in the first, the distance between strip roads was 15 m, and every fifth tree row was harvested using only a harvester (conventional method); in the second, the distance was 21 m, and every seventh tree row was harvested using a harvester and chainsaw (newly proposed method). Additionally, selective cutting was performed between strip roads in both thinnings in the *Pinus taeda* stand, this being the first commercial thinning.

2. Materials and Methods

The study was carried out in a forest located in Parana State, Brazil (25°26′27″ S and 52°55′17″ W). The climate was classified as Oceanic climate/Humid Subtropical, without a dry season with temperate summer (Cfb) (Alvares et al. 2013). The predominant soil type was Lithic Leptosol, with flat to wavy topography, a mean slope of 7.6% and altitude of 600 m.

The first commercial thinning was planned in *Pinus taeda* L. stands planted in a spacing of 3x2 m (3 m between rows and 2 m between trees in a row). Populations were approximately 10 years old in areas with homogeneous soil, relief and site characteristics, with mean values for dendrometric variables of whole stand trees before thinning being: diameter at breast height (DBH) 20.5 cm; height 17.4 m; basal area 33.7 m^2 ha^{-1}; and whole stem of individual tree volume 0.3 m^3.

Thinning was carried out by the mixed method, with systematic and selective harvest of trees from the stand. Two thinning treatments were applied: (1) TH5, consisting of conventional full harvest of every fifth tree row and selective cutting in the adjacent rows, in which the distance between strip roads was 15 m; and (2) TH7, a newly proposed, full harvest of every seventh tree row and selective cutting in the adjacent rows, in which the distance between the strip roads was 21 m (Fig. 1). The machine crane reach was considered, and also the premise that there will be an increased number of trees selectively removed by increasing the distance between the strip roads. However, 50% of the initial stand was harvested together with dead trees with dry crowns for both thinning

Table 1 Parameters of harvested wood assortments in thinning of *Pinus taeda* stands

Assortments	Destination	Dimensions		
		Length, m	Minimum diameter over bark, cm	Maximum diameter over bark, cm
Industrial wood	Saw log	2.7	20.5	35.5
	Veneer log	3.6	20.5	35.5
Energy wood	Fuel wood	3.1	3.5	20.4

treatments. For this, we tried to compensate the number of trees/volume in the thinning intensity in both methods.

The cut to length system was used, with the cut being performed in two ways: TH5, with a harvester; and TH7 by means of a harvester and chainsaw, following the midfield concept, as suggested by Mederski et al. (2018). The harvester was a Caterpillar 315 D, L with an engine power of 64 kW, equipped with mat wheels, a crane reach of 9.2 m and a Log Max 5000 cut head with roll opening of 63 cm, responsible for the felling processing. In addition, a Stihl MS 381 chainsaw with a motor of 3.95 kW, 6.6 kg of weight without fuel, and a 40 cm long bar was used.

The extraction was performed by a Caterpillar 564 model forwarder equipped with tires, 6x6 WD, engine power of 127 kW, maximum crane reach of 6.9 m, an effective claw area of 0.6 m^2, and a load compartment capacity of 13.6 t.

The maximum extraction distance traveled by the forwarder was 200 m, and complete load filling occurred every 50 meters. Thus, the extraction distances evaluated were 50, 100, 150 and 200 meters.

Three types of assortments were processed from the harvested trees: saw logs, veneer logs and fuel wood. Shorter saw logs (2.7 m) and longer veneer logs (3.6 m) were of the same diameter range, while fuel wood (3.1 m long) started from as small diameter as 3.5 cm over bark (Table 1). There were two separate forwarding cycles: cycle 1: saw logs and veneer logs were forwarded at the same time in only one trailer; and cycle 2: forwarding of fuel wood only.

A pilot study was conducted to define the sampling procedure, seeking the minimum number of observations necessary (n) to obtain a maximum error of 5%, using the equation proposed by Murphy (2005):

$$n = \frac{t^2 \times Var(WCT)}{\left(E \times \frac{WCT}{100}\right)^2} \tag{1}$$

Where:

t Student's t-value

$Var(WCT)$ variance of the work cycle time

E level of precision required

WCT mean work cycle time, minutes

A technical analysis was performed using a time-motion study, where the working cycles were divided into five elements (Table 2).

Machine utilization ($Util$ %) refers to the portion of workplace time when a machine was used to conduct the intended function of the machine (Björheden and Thompson 1995), being determined by eq. (2).

$$Util\,\% = \frac{PMH}{SMH} \times 100, \% \tag{2}$$

Where:

PMH productive machine hours

SMH scheduled machine hours

Table 2 Forwarder operational cycle elements

Work element	Description
Driving empty	Time between starting the machine shift from the edge of the stand to the first log pile to be loaded inside the stand
Loading	Time between initial crane motion to load the logs and final grapple positioning in the machine bunker
Driving loaded	Time between grapple positioning in the bunker and machine positioning beside log piles located on the stand edge
Unloading	Time between the initial crane motion for log unloading and grapple positioning in the empty bunker, including maneuvers necessary to start the next cycle
Delay time	Time the machine did not perform the previous activities

Productivity (P) was determined in cubic meters of wood under bark per effective working time (hours), obtained by multiplying the number of logs extracted by the average log volume, as obtained by log scaling via the Smalian method, and divided by the hours actually worked without delay time, according to eq. (3).

$$P = \frac{N \times vi}{PMH_0}, \text{ m}^3 \text{ PMH}_0^{-1} \quad (3)$$

Where:

N number of logs extracted in each operational cycle

vi individual mean volume of logs, m^3

PMH_0 productive machine hours without delay time

Fuel consumption (FC) expresses the fuel consumption per unit of the machine nominal power, and was obtained by multiplying the fuel density (g L^{-1}) with the hourly consumption (L h^{-1}), divided by its nominal power (kW). Then, energy yield (EY) was obtained by the ratio between the specific fuel consumption and the mean machine productivity:

$$EY = \frac{FC}{P}, \text{ g kW}^{-1} \text{ m}^{-3} \quad (4)$$

Where:

FC specific fuel consumption, g h^{-1} kW^{-1}

P productivity, m^3 PMH$_0^{-1}$

Operational cost was determined by the methods proposed by Spinelli and Magagnotti (2010). Production cost (PC) was obtained by the ratio of operating costs and machine productivity:

$$PC = \frac{OC}{P}, \text{ US\$ m}^{-3} \quad (5)$$

Where:

OC operating cost, US$ h^{-1}

P productivity, m^3 PMH$_0^{-1}$

The forwarder operator was 31 years old and had 7 years of experience in the operation.

The forwarder total operating cycle times (driving empty, loading driving loaded, and unloading) (replicates) were compared by t-tests (α=0.05) for independent samples for both thinning treatments. The variance homogeneity was evaluated by the F-test (α=0.05), and the Kolmogorov-Smirnov test (α=0.05) was used to verify the data normality.

3. Results

The results of the technical analysis showed that the forwarder had a mean machine utilization of 66% for both thinning methods, and a 6% higher mean productivity in the TH7 method (Table 3). The energy yield in TH7 was 5.3% lower and the production cost was 3.0% lower in TH7.

Table 3 Forwarder technical analysis in the thinning methods applied in *Pinus taeda* stands

Thinning method	Util %	P, m^3 PMH$_0^{-1}$	EY, g kW^{-1} mcc^3	PC, US$ m^{-3}
TH5	66.0	21.3	0.75	1.97
TH7	66.0	22.5	0.71	1.91

Util % = machine utilization; *P* = productivity
EY = energy yield; *PC* = production cost

The forwarder productivity decreased with increasing mean extraction distance (Fig. 2). Higher productivity was observed when industrial wood was forwarded.

For the thinning method, it was found that forwarder productivity in TH7 was 5.3% higher than in TH5 at a mean extraction distance of 50 m; 6.3% at 100 m; 5.6% at 150 m; and 7.5% at 200 m. These productivity gains were related to the distribution and pile volumes in the stands for each tested thinning method (Fig. 2).

We timed 303 and 345 forwarder working cycles in thinning methods 1 and 2, respectively, requiring 296 and 301 cycles to meet the minimum number of

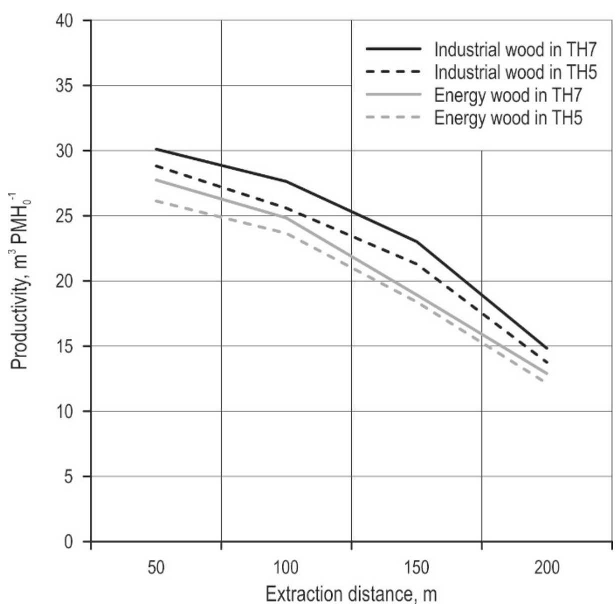

Fig. 2 Forwarder productivity (without delay time) of different wood assortments in relation to the extraction distances and thinning methods applied in *Pinus taeda* stands

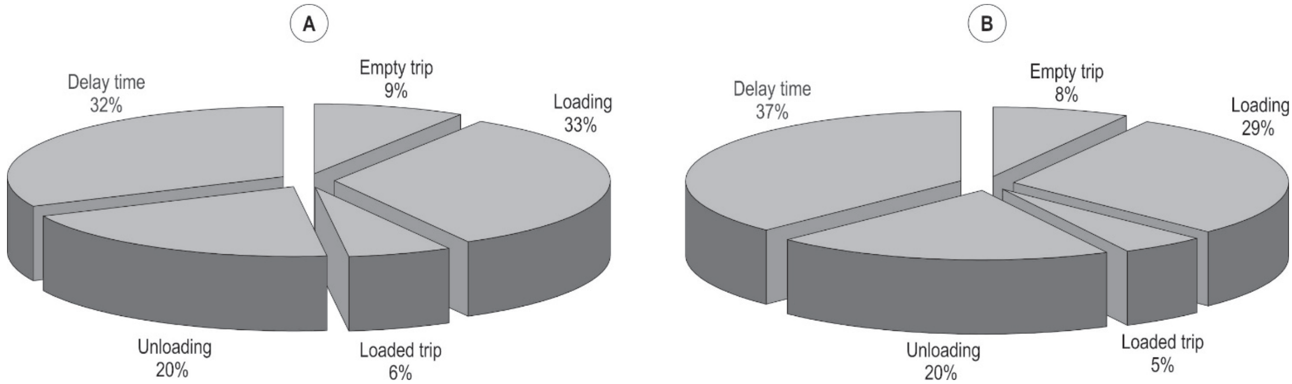

Fig. 3 Shares of work elements when forwarding in TH5 and TH7

observations (α=0.05). The lower share of loading time was observed in TH7 in comparison with TH5; however, there was also a higher share of delay time in TH7 (Fig. 3).

Forwarder work elements such as loading and unloading presented higher percentage participation in the working cycles. Lower participation of the loading element in TH7 was attributed to the increased availability of the log piles along the machine strip roads. This resulted in lower distances between wood piles, allowing the machine to obtain a larger wood volume at each loading location and required less time to perform loading.

Average cycle time duration increased with increasing the extraction distance (Table 4). Less time was consumed in the extraction process of assortment logs than for extracting energy assortment logs. For the thinning methods, it was observed that TH7 consumed less time per working cycle, with a significant difference up to the mean distance of 150 m. The mean distance of 200 m represented the maximum extraction limit.

Table 4 Forwarder working cycles times in thinning methods applied in *Pinus taeda* stands by different extraction distances

Assortments	Extraction distance m	Average time of cycle duration, minutes		Significance
		TH5	TH7	
Industrial wood	50	9.9	9.6	*
	100	10.9	10.4	*
	150	15.4	14.9	*
	200	22.5	21.4	ns
Energy wood	50	10.9	10.4	*
	100	11.9	11.5	*
	150	16.2	15.5	*
	200	23.2	22.9	ns

* = significant ($p<0.05$); ns = non significant

The size of the logs or assortments obtained (industrial or energy wood) are also influential factors observed in this study, since industrial wood only represented 1/4 of the total volume harvested, constituting a situation that affects the operational performance of the machine.

4. Discussion

The pile volume in the field after tree processing by the harvester was the main variable influencing the forwarder operational performance for productivity, energy yield and production costs. In TH7, the forwarder was more efficient due to a higher timber concentration after thinning in the larger 21 m distance between strip roads.

Regarding extraction distance, it was verified that the influence of the thinning method was significant up to the mean distance of 150 m, demonstrating this as the maximum extraction distance limit to gain a benefit in forwarder productivity. Thus, it is possible to adopt 150 m as the maximum distance for optimizing wood extraction through gains in forwarder productivity when applying the TH7 thinning method.

The loading and unloading elements in the study consumed most of the time in forwarder working cycles, which is considered characteristic of forwarding operations. In this way, it can be stated that the forwarder spends more time in the cycle operating passively, either by loading or unloading wood. These results corroborate with the results of several authors such as Simões and Fenner (2010), Lopes et al. (2016), and Rodrigues et al. (2018), who studied this machine in different situations regarding forest species and management regime.

However, it is noteworthy that the time consumed in the loading described above tends to increase due to the difficulties of executing the operation inside the stand, and considering the precautions taken regarding damage to the remaining trees. In addition, Malinovski et al. (2006) mention that the number of lines to be harvested in the systematic thinning and the number of selectively thinned trees are variables with significant influence on the operational performance of wood harvesting machines.

The results obtained herein agree with Mederski et al. (2018), who state that the forwarder has higher productivity and lower costs when working in thinning with a higher distance between strip roads. This is due to the higher concentration of logs in the TH7 method. Manner et al. (2013) state that the number of assortments and log concentration affect the time consumption of forwarding.

Harvesting was not included in this research, however it should be emphasized that the harvester and chainsaw cutting operation in the TH7 method was complex because of the difficulty to control the midfield zone location with the chainsaw between the two harvester trip roads, as well as felling in the trip road direction. These difficulties were similar to those described by Mederski et al. (2018). However, the hypothesis of this study was based on the study by Mederski (2006) conducted in old stands under third and fourth thinnings, in which a chainsaw cutting operation was facilitated.

Therefore, it is noteworthy that the TH7 midfield thinning method can be recommended in older stands for the first commercial thinning, as the logging operation increased productivity and reduced costs. However, the ideal situation in the first thinning would be to carry out studies with modern cutting machines with greater range, avoiding chainsaw cutting problems.

5. Conclusions

Productivity, energy yield and production costs reflected the effects of the thinning method, with TH7 showing the best operating conditions, as well as the possibility of improving productive stand characteristics by reducing the application area of systematic thinning

Loading and unloading elements consumed the most time of the forwarder working cycle. The times of these elements were reduced in the TH7 thinning method, with systematic thinning in the stand of each seventh line

The thinning method effects were reflected in the total times of the forwarder working cycles, being smaller in the TH7 thinning method due to greater log availability in piles along the traffic trail of the machines

The TH7 thinning method showed 6% higher productivity, 5.3% lower energy yield and 3.0% lower production cost compared to the TH5 method. Therefore, the TH7 use in forwarder logging is recommended.

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